Messinian pre-evaporite sapropels and precession-induced oscillations in western Mediterranean climate

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Abstract

Cyclical fluctuations in planktic foraminiferal assemblages have been recognized in the pre-evaporitic Messinian in a marginal basin of the western Mediterranean. The fluctuations coincide with a dominantly precession-controlled sedimentary cyclicity (sapropels). During sapropel deposition, high planktic foraminiferal diversities are indicative of relatively stable marine conditions, while during homogeneous marl deposition low diversities seem to indicate the presence of unfavourable, more saline surface water conditions. The dominance of a precession-related signal indicates that regional climate oscillations rather than (obliquity-related) glacio-eustatically controlled influxes of Atlantic and/or Mediterranean waters are responsible for the faunal fluctuations and sedimentary cyclicity. Our scenario links the persistence of normal marine conditions during sapropel formation with increased rainfall and run-off along the western Mediterranean at times that perihelion occurred in Northern Hemisphere summer. Less favourable, highly saline surface water conditions prevailed during periods of drier climate induced by opposite precessional extremes. The cyclical oceanographic fluctuations could also have governed periodic reef growth along the margins. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Sorbas basin (Fig. 1) formed part of a mosaic of marginal basins located along the Betic Corridor which connected the Atlantic and Mediterranean during the Late Miocene (Fig. 2). In the course of the Messinian, water exchange between the Atlantic and Mediterranean, and between the peripheral basins of southeastern Spain and the open Mediterranean, became restricted.

Throughout the Pleistocene the glacio-eustatic fluctuations, resulting from changes in the Earth's orbital configuration, have critically controlled the hydrography of marginal basins. Recently, Thunell et al. (1988) and Hemleben et al. (1996) have recognized in the Red Sea remarkable changes in the planktic foraminifera assemblages during the Pleistocene. At times of (glacial) sea-level lowstands, water exchange with the Arabian Sea via the Bab el Mandeb Strait was severely limited, resulting in a dramatic increase in surface water salinity. Such salinity fluctuations were also controlled by preces-
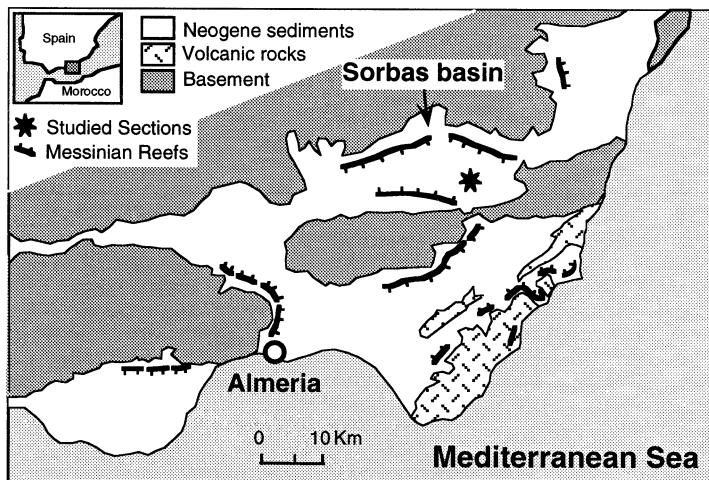

Fig. 1. Map of SE Spain with the location of the Sorbas basin and the section studied. Messinian reef distribution based on Dabrio et al. (1981).

sion-related variations in monsoonal activity that interfered with glacio-eustatic fluctuations, giving rise to parallel changes in planktic foraminifera abundance and diversity. During full glacial maxima, planktic foraminifera vanished completely from the central Red Sea, while at times of climatic optima planktic foraminifera were more abundant and diverse (Thunell et al., 1988; Hemleben et al., 1996).

As in the Pleistocene Red Sea, restriction rendered the marginal basins of SE Spain highly susceptible to local climate variations and global eustatic changes during the Late Miocene. The increasing restriction culminated in the late Messinian with cyclic evaporite deposition during the final stage of the Messinian Salinity Crisis.

2. Precession-controlled sedimentary cyclicity

The Abad marls were deposited in the central part of the Sorbas basin between 7.2 and 6 Ma according to the Astronomical Time Scale of Hilgen et al. (1995). At times of marl deposition in the deeper
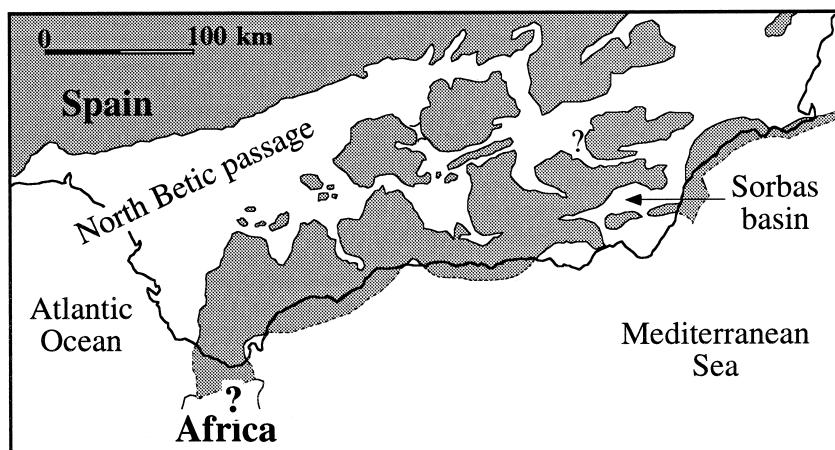

Fig. 2. Palaeogeographic reconstruction of the north Betic passage near the Tortonian–Messinian transition (modified after Serrano, 1975). Dashed lines = approximate southern extent of the exposed region.

central part of the basin, reef growth progressed along the northern and southern margins (Martin and Braga, 1994; Braga and Martin, 1996).

The Abad marls are overlain by evaporites of late Messinian age (Dronkert, 1977; Martin and Braga, 1994; Braga and Martin, 1996). These marls show a distinct sedimentary cyclicity. The overall periodicity of about 23 ka of the cycles (Sierro et al., 1996), estimated through detailed biostratigraphic and cyclostratigraphic correlations to astronomically dated sections in the eastern Mediterranean (Hilgen et al., 1995; Krijgsman et al., 1995; unpubl. data), unambiguously show that this cyclicity was primarily controlled by the astronomical cycle of precession.

The Abad marls can be divided into a lower and upper Abad separated by a slumped interval (Sierro et al., 1996) (Fig. 3). In the lower Abad, cycles are characterized by an alternation of homogeneous grey marls, 2 to 4 m thick, and opal-rich, indurated beds with a thickness of 30 to 50 cm. The same pattern persists in the upper Abad, but a laminated brownish organic-rich layer (sapropel, following the terminology of Hilgen et al., 1995) occurs in the middle part of the homogeneous marls.

In this paper, we focus on the upper Abad that extends from 6.6 to 6.2 Ma. These ages are based on a preliminary astronomical calibration of the sedimentary cycles.

3. Material and methods

Twenty precession-related sedimentary cycles have been sampled (Fig. 4), although the uppermost cycles, deposited immediately prior to the gypsum, have not been studied.

The twenty cycles were analysed in detail for planktic foraminifera. Approximately 8–9 samples per cycle were studied, with a resolution of one sample every 2.5 ka. After drying and weighing, samples were washed and sieved through 150 and 62 μm, but only the 150 μm residues were considered for counting. Residues were split to get a fraction of around 250 planktic foraminifera specimens that were identified and counted. The number of planktic foraminifera per gram was calculated by extrapolating the number of specimens in the split to the whole residue. Diversity was calculated using the Margalef index.

Around 40 specimens of *Globigerina bulloides* were picked and ultrasonically cleaned for the oxygen isotope analysis. The organic matter was destroyed by heating up to 400ºC under vacuum during 2 h. The samples were then introduced in the Sira-II (VG) spectrophotometer with orthophosphoric acid at 25ºC. The results are expressed in PDB (Pee Dee Belemnite standard).

4. Results

Extreme fluctuations in the planktic foraminiferal assemblages can be recognized in the cycles (Fig. 4). *Globigerinoides obliquus*, *Globigerinoides sacculifer*, *Orbulina universa* and *Globigerina apertura*, species of planktic foraminifera living today, or equivalent to forms currently proliferating in warm-oligotrophic waters (Be, 1977; Luz and Reiss, 1983; Hemleben et al., 1988; Pujol and Vergnaud Grazzini, 1995), dominate the fauna in the middle and upper part of the sapropels. On the contrary, *Globigerina bulloides*, *Turborotalita quinqueloba* and the Neogloboquadrinids are dominant in the homogeneous marls and indurated layers (Fig. 4). This group of species is characteristic of cold-eutrophic waters (Be, 1977; Luz and Reiss, 1983; Hemleben et al., 1988; Pujol and Vergnaud Grazzini, 1995). The ratio between warm-oligotrophic and cold-eutrophic planktic foraminifera is shown in Fig. 4 and denotes the ratio between the warm-oligotrophic foraminifera and cold-eutrophic plus warm-oligotrophic planktic foraminifera. Since most of the species are in one of the two groups, values close to 1 mean that the warm-oligotrophic planktic foraminifera form nearly 100% of the assemblage, while values of 0 occur when cold-eutrophic foraminifera are around 100% of the association (Fig. 4).

The benthic foraminiferal assemblages of the lower Abad are dominated by *Cibicidoides* spp., *Uvigerina peregrina* and sometimes *Planulina ariminensis* indicating normal, relatively well oxygenated bottom water conditions. In contrast, the upper Abad microfaunas are indicative of more restricted conditions. In the homogeneous intervals, *Brizalina* spp., *Rectuvigerina* spp. and *Bulimina elongata* are usually the most abundant species in the homogeneous intervals indicating the existence of oxygen-poor, organic-rich waters at the bottom. In the sapropels
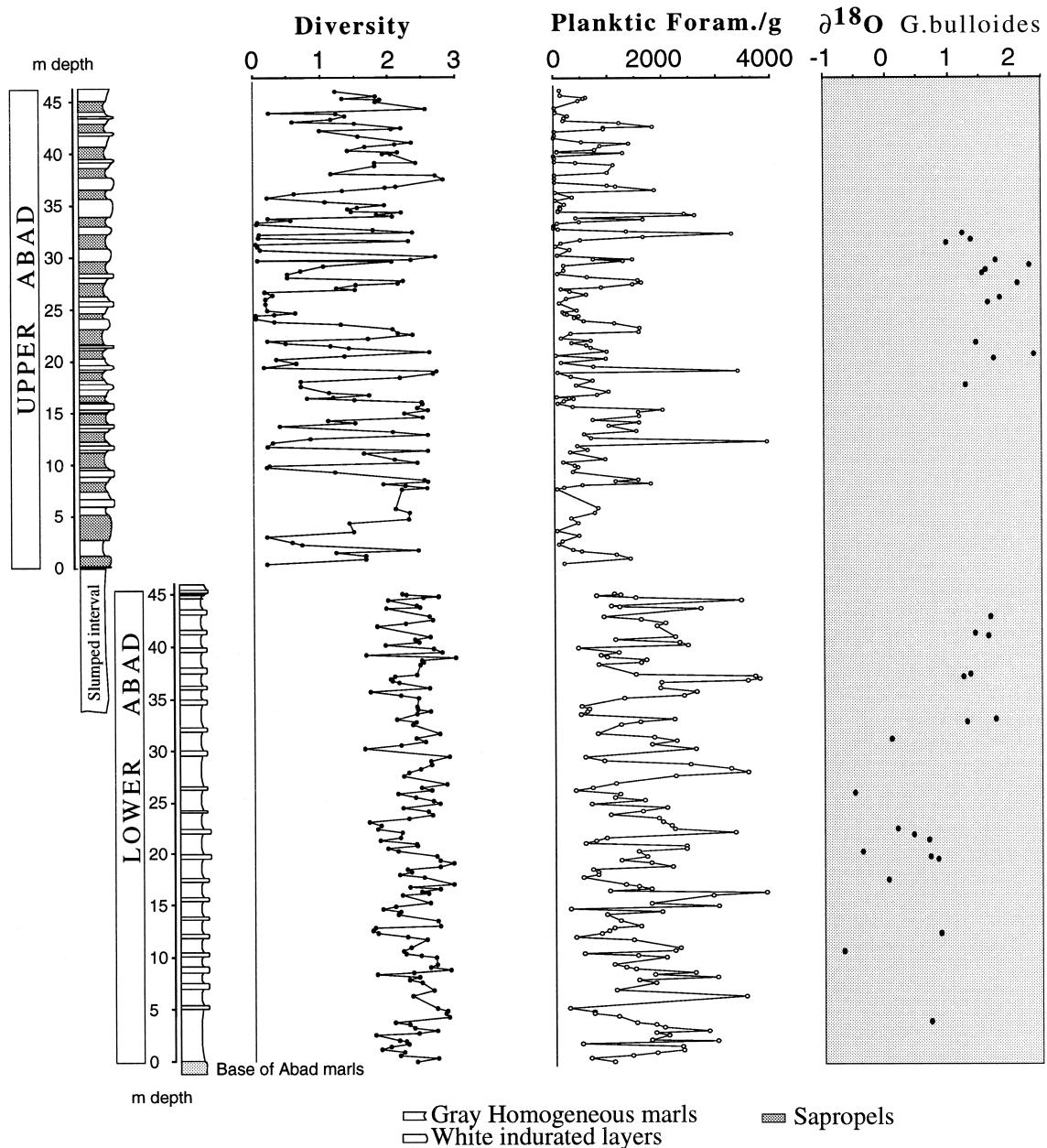
Fig. 3. Evolution of diversity, planktic foraminifera per gram and oxygen isotope data (homogeneous marls) throughout the lower and upper Abad. Diversity index = Margalef index.

benthic foraminifera are usually very rare or totally absent, indicating that the oxygen content was too low to support benthic life.

The most striking observation, however, is that planktic foraminifera which appear with normal di-

versities and abundances in the lower Abad, abruptly reduced in the upper Abad. Planktic foraminifera also periodically experienced extremely hostile conditions, causing them to vanish almost completely in the uppermost part of the section (Figs. 3 and 4).
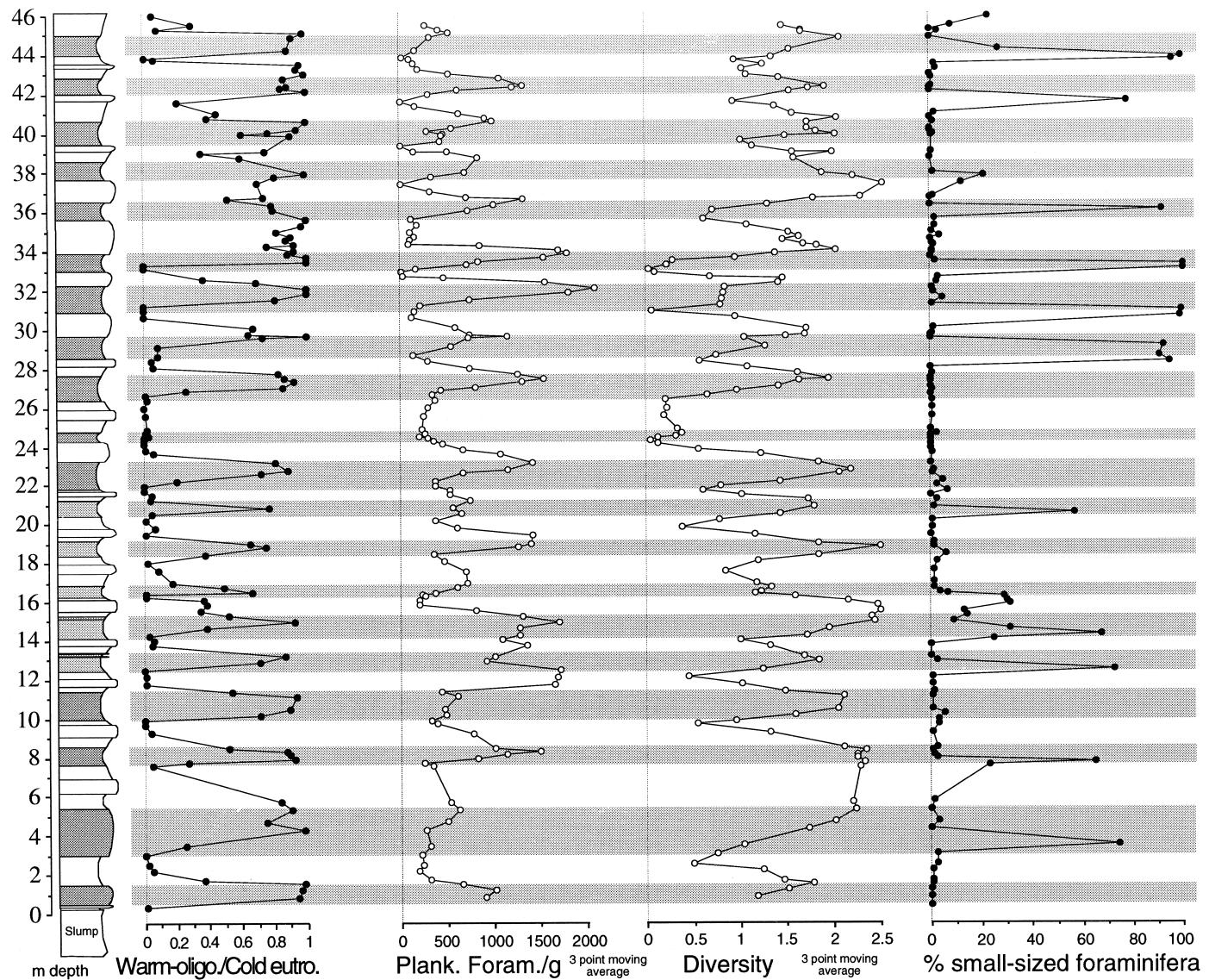
Fig. 4. Relation between sedimentary cyclicity in the upper Abad and planktic foraminiferal assemblages, planktic foraminifera per gram, diversity and percent of small-sized foraminifera. Planktic foraminifera per gram and diversity data were averaged every three samples. Warm-oligo./Cold-eutro = (warm-oligotrophic planktic foraminifera)/(cold- eutrophic + warm-oligotrophic foraminifera) (see text). Legend as in Fig. 3.

Planktic foraminifera reach their maximum abundance near the top of the sapropels; they begin to decrease during the deposition of the homogeneous marls, and almost disappear near the transition from the homogeneous marls to the sapropels (Fig. 4). An exception to this general pattern is found around 12 m where levels very rich in *Globigerina bulloides* occur; they are, however, almost monospecific indicating exceptional conditions favourable for this particular species.

Diversity follows a very similar trend, the maximum number of species is found in the upper part of the sapropels, and only one or two species survive at the transition from the homogeneous marls to the sapropels (Fig. 4). These transitions are sometimes marked by strong peaks of small-sized microfaunas (*Turborotalita quinqueloba*, *Turborotalita multiloba*, *Globigerinita glutinata*).

5. Interpretation

The strong reduction in the diversity and abundance of planktic foraminifera during deposition of the upper Abad (Fig. 3) indicates that water exchange with the normal marine waters of the open Mediterranean was severely reduced. Increasing $\delta^{18}O$ values in the homogeneous marls levels without any apparent change in the warm-water planktic foraminifera also suggests an overall increase in salinity from the lower to the upper Abad. The increase in $\delta^{18}O$ occurred in the upper part of the lower Abad at the level which coincides with the formation of the first sapropels in the Sorbas basin. These older sapropels are found in parallel sections located in the deeper part of the basin. Using cyclostratigraphy in combination with the high-resolution biostratigraphy, the older sapropels can be correlated unambiguously with the uppermost cycles of the lower Abad in our section.

The unfavourable conditions marked by low planktic foraminiferal diversities in the homogeneous marls of the upper Abad are punctuated by episodes of higher diversities in the sapropels (Fig. 4), indicating the persistence of relatively normal marine surface water conditions at those times. However, immediately above the top of the sapropels, conditions became rapidly less favourable for planktic foraminiferal growth, resulting in reduced numbers of planktic foraminifera specimens

per gram and decreasing diversities. These hostile conditions reached a maximum at the homogeneous marl–sapropel transitions, which apparently prevented planktic foraminifera from surviving and reproducing. Several nearly 'aplanktonic zones' occurred (periodically) at homogeneous marl–sapropel transitions in the uppermost Abad, especially from the 33 m level upwards (see Fig. 4). Only the extremely eurytopic small-sized microfaunas could survive (Fig. 4). Similar aplanktonic zones have been recognized in the Red Sea during glacial maxima due to the extreme confinement of the basin at those times (Thunell et al., 1988; Hemleben et al., 1996).

As in the Red Sea, the higher diversities during sapropel deposition could be explained by enhanced inflow of Atlantic and/or Mediterranean waters as a consequence of glacio-eustatically controlled sea-level rises. This inflow of less saline waters at the surface, together with the persistence of strongly saline waters in the intermediate and deep waters of the marginal western Mediterranean basins, could have caused a strong stratification in the water column, preventing bottom ventilation and triggering sapropel formation. On the other hand, during glacial sea-level lowering, water exchange with the Mediterranean and open ocean would have become increasingly restricted and planktic foraminiferal growth progressively inhibited as a consequence of the ensuing high salinity.

However, in most oxygen isotope records from the Messinian (Keigwin, 1987; Hodell et al., 1994; Shackleton and Crowhurst, 1998), significant power is found in the obliquity frequency band of the spectrum and less power in the precessional band. The obliquity-related variations are assumed to reflect glacial cyclicity. Since our records are dominated by precession-related variability, it may be inferred that glacio-eustasy is not primarily responsible for the faunal and sedimentary cyclicity.

Once the eustatic hypothesis is rejected, it can be suggested that sedimentary and faunal cycles were mainly controlled by regional climate fluctuations induced by precessional changes in the orbital configuration as is the case for the most recent sapropels in the Mediterranean (Rossignol-Strick et al., 1982; Rossignol-Strick, 1985; Hilgen, 1991a,b). Enhanced run-off due to monsoonal intensification and increasing wetness of the borderlands has been reported as

the primary cause for sapropel formation in the eastern Mediterranean and Red Sea, both in the Plio–Pleistocene (Rossignol-Strick et al., 1982; Rossignol-Strick, 1983; Hilgen, 1987, 1991a; Thunell et al., 1988; Thunell and Williams, 1989; Rohling and Hilgen, 1991; Rohling, 1994) as well as during the Late Miocene (Nijenhuis et al., 1996). This change in regional climate occurred at times of precession minima when perihelion occurred during the Northern Hemisphere summer (Rossignol-Strick et al., 1982; Rossignol-Strick, 1985; Hilgen, 1991a,b). Recent climatic models (Kutzbach and Webb, 1993) estimate higher summer precipitations for the Northern Hemisphere at times of precession minima.

The overall restricted conditions which existed during deposition of the upper Abad certainly affected deep water renewal in the basin, leading to the formation of oxygen-poor, highly saline deep waters with high nutrient concentrations. Vertical mixing of the water column was further reduced at times of lowered surface water salinities. The ensuing salinity stratification resulted in complete anoxic bottom water conditions, thereby triggering the formation of sapropels. In addition, the salinity stratification contributed to maintain more stable, less saline water conditions at the surface throughout the year. Clearly, the high abundance of oligotrophic calcareous planktic assemblages, both in foraminifera as well as in Coccoliths in combination with the total absence of siliceous microfossils indicate that the oxygen depletion of bottom waters at times of sapropel formation was not caused by (enhanced) productivity. Nutrients supplied by rivers would have been rapidly consumed by the phytoplankton keeping nutrient-depleted waters at the surface most of the time.

Stratification of the water column became periodically unstable when drier climatic conditions started to prevail in the Mediterranean. Under such circumstances (drier climates), average surface water salinities increased as a result of a higher 'excess of evaporation', thereby reducing the vertical density gradient between the surface and the deeper waters. The increasing density of the surface water initiated deep water formation again. This deep water circulation would have favoured the pumping of deep waters from the marginal basins to the open Mediterranean or Atlantic. The rapid renewal of deep waters supplied the oxygen necessary to remineralize

organic matter in the water column and permit the recolonization of the bottom by the benthic fauna. The renewed sinking of surface waters and consequent deep water convection probably drove nutrients into the euphotic layer, creating favourable living conditions for cold-eutrophic-water planktic foraminifera. However, despite the favourable conditions, the abundance and diversity of planktic foraminifera was reduced. This apparent contradiction may be explained by the high levels of eutrophication, favouring the blooming of other planktic groups, such as the siliceous plankton. Siliceous plankton is usually abundant in the homogeneous intervals. In addition, the unstable water column and more saline surface water conditions were also unfavourable for planktic foraminiferal growth (Hemleben et al., 1988, 1996).

This astronomically driven, faunal cyclicity is not an isolated case in the Mediterranean during the Messinian. Similar periodic fluctuations are also recorded in the Tripoli formation of Sicily where very low diversities and intervals devoid of planktic foraminifera are always related to the claystones alternating with the laminites (Pedley and Grasso, 1993; Suc et al., 1995; Sprovieri et al., 1996a,b).

This cyclicity is the prelude to that recorded in the Mediterranean evaporites, where marl beds are interbedded within the gypsum layers. These marls are probably the equivalent to the sapropels of the Abad marls, suggesting the periodical recurrence of stages of enhanced run-off during evaporite deposition in the Mediterranean.

6. Was reef growth punctuated by precession?

The growth of reefs during the Messinian along the margins of western Mediterranean peripheral basins is well known (Esteban, 1979; Dabrio et al., 1981; Martin and Braga, 1994; Braga and Martin, 1996; Braga et al., 1996) (Fig. 1). In the Sorbas basin, they were coeval to the upper Abad marls (Martin and Braga, 1994; Braga and Martin, 1996).

How did the reefs respond to these drastic hydrographic fluctuations in the basin? Although *Porites*, the main reef-builder in the Sorbas basin, is more tolerant to salinity changes (Esteban, 1979) the reefs of the Sorbas basin have usually been interpreted as living in normal marine waters (Riding et al., 1991).

According to our conclusions derived from basinal successions, oceanographic conditions were optimal for reef growth along the margins at times of sapropel formation; salinities decreased due to the onset of more humid climates and normal marine stable conditions prevailed in the basin. The stability of the water column and the high temperatures and low availability of nutrients that favoured the presence of warm-oligotrophic planktic communities should also have favoured reef growth. Both reef corals and symbiont-bearing, oligotrophic planktic foraminifera use algae to trap nutrients in shallow, warm and well illuminated waters. Such warm-oligotrophic and well illuminated waters exist today in the Red Sea, where reefs are well developed and flourishing in the margins of a sea that is characterized by plankton communities dominated by *Globigerinoides ruber*, *Globigerinoides sacculifer* and *Orbulina universa*.

On the contrary, during cold-eutrophic stages, the unstable conditions and the intensification of vertical mixing in the basin drove nutrients upwards and reduced surface temperatures. These conditions favoured the blooming of phytoplankton (i.e. diatoms, small prinsiacea, etc.) and the symbiont-lacking planktic foraminifera. Lower temperatures, enhanced salinities and higher levels of eutrophication in the water column were probably unfavourable for reef growth in the basin. Higher levels of eutrophication are often associated with increasing turbidity that reduce light intensity and consequently the reef growth. Even though the reefs could have survived these conditions, it can be argued that they were probably unable to tolerate the highly adverse conditions that inhibit the planktic foraminiferal growth during the stages immediately preceding sapropel formation.

The high-frequency cyclicity (C2 cycles) recognized by Braga and Martin (1996) in the northern margin of the Sorbas basin could be related to the astronomically driven oceanographic fluctuations described in this paper. These cycles characterized by reef aggradation and progradation are limited by consecutive wedges of calcarenite beds indicating destruction of former or coeval reefs (Braga and Martin, 1996). The same authors infer that these cycles could be related to the Earth's orbital cycle of precession, but interpret the calcarenite beds as the lowstand deposits of C2 cycles.

7. Conclusions

A high-resolution quantitative study of planktic foraminifera in the pre-evaporite marls of the Sorbas basin (western Mediterranean) allowed us to recognize long-term and short-term faunal changes. A strong reduction in the diversity and abundance of planktic foraminifera together with the increase in oxygen isotope values in the middle part of the section clearly indicates that water exchange with the normal marine waters of the open Mediterranean was severely reduced.

In the upper part of the section short-term sedimentary cycles have been identified by the alternation of homogeneous marls and sapropels which are characterized by extreme fluctuations in the planktic foraminiferal assemblages. Planktic foraminifera characteristic of warm-oligotrophic waters are very abundant during sapropel deposition, while foraminifers usually living in cold-eutrophic waters are dominant during the homogeneous marls. Besides, higher diversities and abundances usually occurred towards the top of the sapropels, whereas the lowest diversities and abundances are invariably linked to the transitions between the homogeneous marls and the sapropels. It is at these transitions that conditions where most unfavourable and when planktic foraminifera almost disappear in several cycles of the uppermost part of the section.

The dominance of a precession-related signal indicates that regional climate oscillations rather than (obliquity-related) glacio-eustatically controlled influxes of Atlantic and/or Mediterranean waters are responsible for the faunal fluctuations and sedimentary cyclicity. During sapropel deposition the increasing humidity of the Mediterranean climate induced water stratification, due to the persistence of less saline waters at the surface. Planktic foraminifera characteristic of warm-oligotrophic waters were very abundant at this time. This situation would have periodically become unstable when drier climates prevailed in the Mediterranean. The increasing salinities of surface waters would have triggered the mechanism of deep water formation, breaking the stratification. The increase of cold-eutrophic-water planktic foraminifera during these intervals indicates nutrient-rich waters in the surface due to intense deep mixing in the water column. Diversity de-

creases due to the higher salinities and more unstable conditions.

It is proposed that oceanographic conditions during sapropel deposition were favourable for reef growing along the margins of the basin, while these conditions were probably less favourable during the sedimentation of the homogeneous marls and specially at the transitions between the homogeneous marls and the sapropels.

Acknowledgements

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